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Folding tidal turbine as an innovative concept toward the new era of turbines

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ABSTRACT

Research and development of tidal current turbines has undergone significant growth since the past decades. The trials and errors have led to the improvements for various aspects of tidal current turbines. One of the remaining problems of tidal current turbines is the difficulties in transportation and installation. The concept of folding tidal turbine was proposed to provide a solution for the ease of transportation and installation in 2010. Folding tidal turbine has the foldable parts of blades, shaft, connecting rods and outer box compared to the rigid structure of a conventional turbine. The current study discusses the components of folding turbine, rigidity of structure, performance, working concept, efficiency, material, electrical aspects, environmental impacts and prevention of marine corrosion. Previous works proposed the costs for transportation and installation of a conventional tidal turbine were 30% of the total cost. Folding tidal turbine is estimated to reduce 20% of the total cost with a shorter installation time.

Contents

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1. Introduction

The population of the world has exceeded seven billion in 2013 [1], which led to a higher pressure to meet the ever-growing energy demand. Non-renewable sources have been widely used for the operations of machines to boost the economic development in the past centuries. The primary energy consumption of the world consists of 35.6% on oil (3952.8 million tons of oil equivalent, Mtoe), 23.8% on natural gas (2637.7 Mtoe), 28.6% on coal (3177.5 Mtoe), 5.6 % on nuclear power (622 Mtoe) and 6.4% on hydroelectricity (709.2 Mtoe) [2], as shown in Fig. 1. The use of fossil fuels gives negative impacts to the environment and human health causing diseases such as skin cancer, respiratory diseases etc. Fossil fuels are also less reliable in long term due to limited reserves [3] and the price surges with increasing demand. Hence, renewable energy should be promoted for sustainable developments.

Renewable energies including biomass [4], solar power [5], wind power [6] and marine renewable energy [7,8], are the natural resources which can be recovered in a measurable time period. These resources are more environmental friendly compared to the non-renewable resources. The depletion of inland resources leads the exploitation of the ocean energy for electricity generation [9,10]. Theoretically oceans can produce 20,000 to 92,000 TW h/year of electricity to match the current world consumption of 16,000 TW h/year [11]. Tidal currents [12–14], waves [15], salinity gradient [16] and temperature gradient [17] are different forms of energy that can be extracted from the ocean. Machines were developed from time to time in order to extract these energies depending to the site characteristics. This process is essential to reduce the cost and installation time when harnessing the ocean energy.

Tidal barrage is an earliest method designed to harness tidal energy [18–20]. As this method is analogous to a dam construction, tidal barrage may cause the similar environmental impacts faced by dam. Scientists introduced tidal turbine to capture the kinetic energy of flowing water in a more environmental friendly way [21]. Tidal turbines are designed to harness kinetic energy from tidal currents caused by gravitational interaction among the sun, the moon and the earth [22,23]. The implementation of tidal turbines prevents the construction of barrages and impounding of water [24]. Thus, tidal turbine received more attentions in the past decades [25].

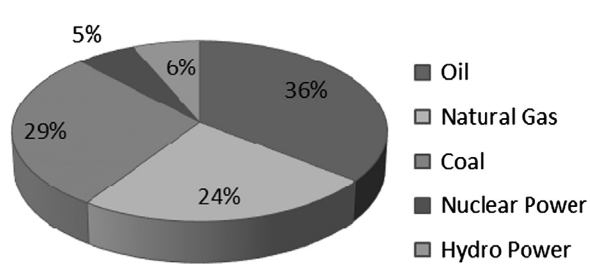

Fig. 1. World power generation from various energy sources (unit in Mtoe).

Marine Current Turbines Ltd. [26] installed a 1.2 MW tidal turbine known as SeaGen in Strangford Loch, Northern Ireland. SeaGen has been connected to the national electricity grid and it is promised to delivered 6000 MW h/year. SeaGen produced more than 7 GW h of electricity to date since 2008 [27]. The cost of production is still the main considerations to further push forward the tidal electricity. Researches to reduce the cost mainly focus on the turbine performance and manufacturing cost. The breakdown cost for the transportation and installation is 30% of the total cost according to the experiences of SeaGen. The size of turbine is large to make the transportation and installation costly [28].

Folding tidal turbine (FTT) is proposed to overcome the installation and transportation problems by Dr. Lam with patents of CN101907054-A [29] and CN201896695-U [30] in 2010. The concept of FTT is inspired by the foldable characteristics of folding bikes and airplane in aircraft carrier (see Fig. 2). Two folding turbines are proposed including the vertical-axis [31] and horizontal-axis turbines [32], as shown in Fig. 3(a) and (b). Vertical-axis folding turbine is the main focus of this paper. For a vertical-axis folding turbine, turbine components of blades, shaft, connecting rods and outer box can be folded up to a smaller size. The outer box of FTT can be opened up to form a base during the installation of turbine. In this paper, conventional tidal turbine is initially discussed and followed by the proposal of FTT. The comparison between FTT and CTT is made to identify the opportunities and challenges on implementing FTT.

2. Highlights of tidal current turbines

In the past decade, tidal current turbines have re-captured the attention of engineers and researchers. Most of the developed and developing countries are exploring the available renewable resources for sustainable power generation. In [33] the authors have made efforts to explore the potential of straits of Malacca. Different design of turbines has been proposed, built and tested [34–36]. Many researches have also been conducted to gain more insights into tidal current turbines. Readers are referred to [37]

Fig. 2. Folding wing of airplane.

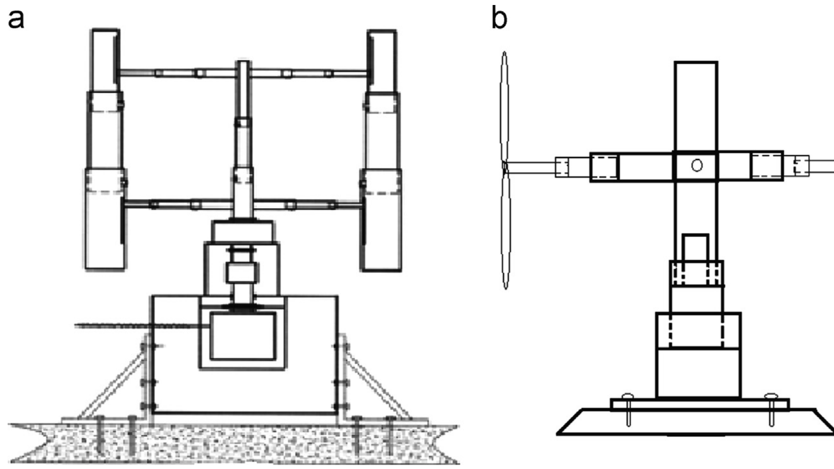

Fig. 3. Schematic representations of FTTs, (a) vertical-axis; (b) horizontal-axis.

for latest review on the research in tidal current turbines. Generally, those researches cover energy resource assessment, performance of turbines and development of novel design [37]. One of the milestones would be the commissioning of the first commercial-scale grid connected SeaGen as mentioned in Section 1 [27]. The success of SeaGen has proven the viability and workability of tidal current turbines. Therefore, other countries apart from UK, which possess significant tidal current energy, have also started to look into the feasibility of tidal current turbines in their country.

The first step required for deployment of tidal current turbines would be a proper energy resource assessment of potential sites. Several methods have been proposed by researchers to assess the potential tidal energy and the extractable power by turbine [37]. This part is crucial in order to identify and select the potential site, as well as to fully utilize the tidal energy, especially for tidal current turbine arrays. Proper understanding on the available energy resource is the key to the appropriate design of tidal array layout, which could eventually generate the designed power. The second step is the design of turbine based on the flow characteristic of the selected site. This part involves design of blade, selection of appropriate components (such as types of generators and types of foundations), selection of materials and design of monitoring and maintenance system.

Certainly, there are problems faced in these steps. For energy resource assessment, different methods yield different estimation and therefore different tidal current turbine array's layout. For design of turbine, although the market tends to favour horizontal-axis turbine (as a result of the knowledge from wind turbine study), researchers have a different idea towards it [38]. There is no consensus yet on whether horizontal-axis or vertical-axis will be the best option for tidal current energy. From time to time, researchers also proposed different designs of tidal current turbines which address different issues. For examples, the various designs include: introducing duct for flow acceleration purpose [39], contra-rotating turbine for maintenance-friendly purpose [40] and gearless turbine for cost minimization purpose [41].

While more focus has been given to the operation and maintenance issue of tidal current turbines, it is important to consider the challenges associated with transportation and installation. Delivery of tidal current turbines from factory to sites requires costly transportation. Some more, there is restriction on the size of objects that can be transport on the road. The installation of tidal current turbines is also very difficult as the size is big and it involves underwater installation. These works will become more challenging and costly when it comes to the transportation and installation of tidal current turbine array. To date, less focus has been given to these challenges either in industry or academia. Hence, the idea of FTT is brought up again to address these challenges.

3. Folding tidal turbine

The implementation of FTT depends on the understandings of the components, material used, performance, installation, maintenance, cost, environmental impacts and power transmission. This section starts with the introduction of various components of folding turbine, the material used for these components and the theoretical efficiency of folding turbine. The installation and maintenance procedures are described and followed by the considerations of cost, environmental impacts and power transmission.

3.1. Components of folding tidal turbine

FTT consists of foldable and non-collapsible parts. Foldable parts are blade, shaft and outer box, which can be opened up during the installation. The non-collapsible parts are gearbox and generator which are analogous to CTT. The detailed introductions are made in the following sections.

3.1.1. Blades

Blades are the most significant part of the rotor. The designing of the blade is crucial as the performance of the turbine depends upon it and among all the parts of the turbine, blades are highly exposed to water. In this section the blade size for FTT is discussed. The original design of the vertical-axis FTT consists of three blades as commonly practiced for wind turbines. Three-bladed turbine is believed to be an optimum configuration in terms of stability and performance [42]. However, the blade number can be varied from two to ten, depending on the needs. The guideline for the FTT is still unavailable at this stage.

Previous studies suggested that three-bladed turbine is more efficient at high rotational speeds and these blades should be shorter to spin faster [43]. The blades of FTT are designed to be shorter and wider compared to CTT in order to resist higher bending moment due to the foldable feature [44,45]. Fig. 4 illustrates the blades consists of three connected parts to make it extensible. The extensible feature makes the blade more flexible and smaller in size compared to the CTT. The light material is proposed to be used to allow a faster rotational speed. A folding

Fig. 4. Extensible blades of folding tidal turbine.

turbine of 1.5 kW is used throughout the discussion. However, in this section the power output is assumed as 1.2 MW for easy understanding of the analogy with Seaflow and SeaGen.

The diameter of rotor can be calculated by using Eq. (1).

$$P = \frac{1}{2} C_p \rho A V^3 \tag{1}$$

where P is power output (W), C_p is power coefficient of the rotor (assumed as a standard factor of 0.40), ρ is density of seawater (assumed as 1029 kg/m^3), V is incoming flow speeds (assumed as 2.5 m/s) and A is flow contact area (m^2).The flow contact area is the multiplication of height (m) and diameter (m) of turbine, which is the maximum area contacting to the incoming flow. The term of flow contact area is used for a vertical axis turbine throughout the paper instead of the swept area used for a horizontal axis turbine.

By substituting C_p of 0.4, ρ of 1029 kg/m^3 and V of 2.5 m/s into Eq. (1), the flow contact area (A) of 373 m^2 is required to harness 1.2 MW of electricity. The proposed area is sensible compared to the swept area of Seaflow and SeaGen. The swept area of 300 kW Seaflow is 95 m^2 for a 11 m-diameter rotor, whereas the swept area of 1.2 MW SeaGen is a total of 402 m^2 for two 16 m-diameter rotors. Hence, the height and diameter of FTT can be calculated based on the rated power. A common ratio of 2:1 for height and diameter is proposed for the dimension of FTT. The height of 28 m (round off for 27.3 m) and diameter of 14 m (round off for 13.66 m) are proposed for the deep water. For the shallow water, a size of 24 m (round off for 23.7 m) for height and 16 m (round off for 15.8 m) for diameter is proposed with a ratio of 1.5:1 for height and diameter. The area variations between the proposed FTT and CTT are mainly due to the value of parameters used in the calculation. The efficiencies for the power train, gearbox, generator and transmission are not included into the consideration of power output.

3.1.2. Shaft

The shaft connects the rotor to the generator in order to transfer the rotational force to generator. The shaft of FTT comprises of three connected elements to make it extensible, as shown in Fig. 5. The combination of extensible shaft and blades enables the height control for turbine and space saving during transportation and installation. Hence, the height of turbine can be adjusted according to the characteristics of various sites and provides ease in the power regulation of FTT.

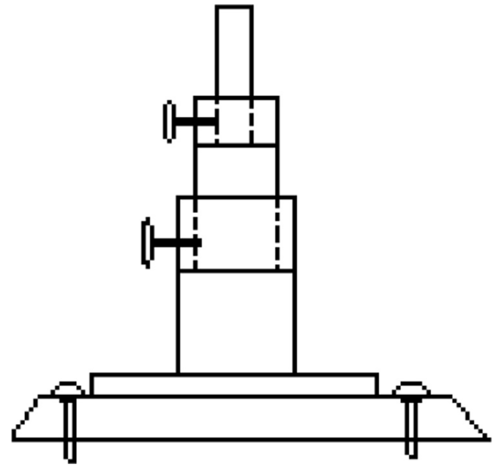

Fig. 5. Foldable component of shaft rod.

3.1.3. Outer box

The outer box is used as a protection unit for FTT during transportation and acts as a base on the sea bed during the installation. Once FTT reaches the sea bed, the box is being opened up as a base for the installation of turbine. The box also contains the cylindrical foundation to make the foundation more rigid and stable. The upper flap consists of two symmetrical parts from the top view, as shown in Fig. 6. These two parts ensures the stability of turbine when being opened up at the seabed.

3.1.4. Gearbox

The rotor transfers kinetic energy of the incoming flow to produce electric power using a generator. The turbine shaft rotates at a lower speed depending upon the available water velocity and a gearbox is normally needed to speed up the rotation to intensify the electricity generation. The speed of tidal flow is variable depending on the time period and gearboxes are therefore provided for the both sides of generator [46,47]. The gearboxes and generator form one collective unit in FTT. Likewise a SeaGen, rotors are directly mounted to the shaft transferring the rotation to gearbox. The rotation is speeded up to a desire speed using gearbox which in turn drives the generator. The powertrain including gearbox and generator is enclosed in a nacelle. The proposed gearbox is a step-up epicyclical gearbox. This gearbox obtains the rotation from rotors through parallel shafts. The increased speed results in a higher efficiency of electricity generation. A compact and light gearbox with a low cross sectional area is appropriate for FTT as those in SeaGen.

3.1.5. Generator

Generator converts kinetic energy of tidal currents into electrical energy. The use of both synchronous and induction generator is equally popular. SeaGen, SeaFlow and Kinetic hydropower system tidal current turbines used induction generator while Encurrent turbine and Cycloidal turbine used synchronous generator. Kobold and Gorlov turbines used both induction and synchronous generator. A review on the usage of generators for different turbines is discussed in [48]. The selection of generator from all the kinds depends upon the requirement of the site and

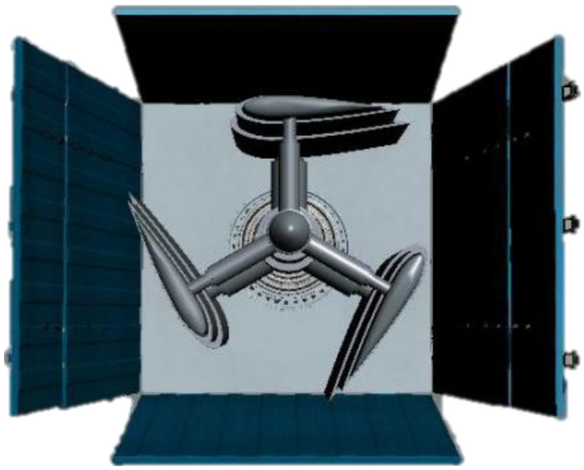

Fig. 6. Outer box with a folding turbine.

the capacity of the power harnessed. Under induction generator the use of doubly fed induction generator (DFIG) is widespread. The reason can be attributed to the capability of DFIG to operate during severe grid faults, maintenance of constant output during fluctuating tidal flow, optimum power factor and extraction of power from both stator and rotor winding [49]. However, the use of slip rings and gears are the cons of DFIG [50].

The use of synchronous generator is more focused towards the sites with low water current velocity. The features like full speed range, possibility to avoid gearbox, brushless, no use of power inverter and complete control on reactive and active power makes PMSG a suitable choice for tidal current turbine. Besides, PMSG is comparatively expensive requires rare-earth magnets, full scale power converter and multi-pole generators which adds up in the cost. Furthermore, to covert the multi-frequency power generated by PMSG, power electronic units are required. The chances of failure of power electronic unit are 12.96% (failure/turbine/year) while the chances of failure of a gear box are 5.6% [51]. Hence for FTT, DFIG is proposed.

3.2. Material

The material used for tidal turbines must be capable of working under the conditions of high pressure, abrasion caused by the sand carried by the flow, pH levels and salinity that can cause corrosion. Hence, appropriate material is required to handle such conditions and micro-biological attachments which cause sheer stress. Besides, cavitation is one of the concerns while choosing the material for FTT. Cavitation is the formation and immediate implosions of bubbles formed in liquid, i.e. small liquid free zones as consequences of forces acting upon the liquid. The bubbles formed due to such changes bursts and cause cavities on the surface of turbines. Hence, it is important to prevent the turbine from cavitation [52]. The requirement of various parts and the suitable material for them is discussed in this section.

3.2.1. Material for blade, shaft and rods

The material which was earlier used for tidal turbines was stainless steel as it does not really corrode, rust or stain with water as compared to the ordinary steel. However, stainless steel is not fully stain proof most notably under low oxygen, high salinity or poor circulation environment. This kind of environment is common under sea where the turbine is being set up. The main advantage of using stainless steel is it has antibacterial properties. The introduction of new alloys like high strength low alloy steel (HSLA) [53] solved the problem of corrosion to a great extent. A type of HSLA uses Ni, Cu and Si as the alloying elements for making the dock walls, sea walls, bulkheads and parts of turbine as the corrosion resistance it is two to three times greater than that of carbon steel in the splash zone of marine structure. Hence, FTT is made up of HSLA. If a large FTT is used, the composite material may be useful as proposed for SeaGen.

The parts which are used for the movement of fluid usually get corroded first [54]. It means special attention is needed in the making of the blades due to the movement of the fluid. Studies have shown that the lower part of the blades get damaged first due to some manufacturing design defect. Thus, the usage of several other alloys is important where traces of plastic are used in the manufacturing of blades.

In the case of FTT where the number of welds increases, there is a need to protect the parts from being corroded at such places. A metallurgical evaluation shows that a high strain, work hardening austenitic stainless steel produces superior resistance to cavitation erosion. Cavitation occurs at various degrees in all type of fluid handling equipment. In FTT, the rate of cavitation is higher as it has more space for bubble formation which causes cavitation. Cavitation causes surface penetration of up to 10 mm per year to critical components like turbine blades [51]. The severe cavitation can be avoided by the use of high carbon and cobalt base alloys. However, these types of alloys are more cracks sensitive. In case of FTT, it is not recommended to use these alloys.

3.2.2. Material for outer box

The outer box of FTT will have many qualities. The use of cushioned packing is removed in FTT and it will be assured that the outer box will protect all the inner parts from damage and mishandling. Hence, the box should be strong and stable. The box opens up during the installation and forms a surface over the sea bed. The box should be stable and non-corrosive to meet such requirements. The properties which are required for the outer box are: handling high stress and noncorrosive. There are a few aluminium alloys which may hold such properties but still it cannot be made as strong as steel alloys.

Under the condition of high stress, steel does not break. However, it may bend and can be easily repaired if damaged. The composition of outer box material is varied from blade composition. Outer box rigidness is more important than flexibility. The parts which have welds and bolts are more prone to corrosion. The use of Cavitec [55] (Cavitec is the trade name of Eutectic-Castolin) will be beneficial to solve the problem of corrosion of welds. The drawback of using steel based alloys is the high cost. In spite of this, steel based alloys prevent corrosion and are maintained easily, hence, their use is significant.

3.2.3. Material for foundation

Foundation of the turbine is the structure built to install and support the turbine inside the sea. The role of the foundation is to support the heavy rotor and power train, resist the cyclic tidal forces and marine environmental degradation for longer periods [56]. The foundation used for tidal turbine is tripod, gravity based and mono-pile structure which is either made up of steel based alloys [57] or concrete. The structure goes inside the sea bed and hence the coating is different from the other parts. The requirement is to lower the effect of biological formation, wear & tear and corrosion caused by water, sand and microorganisms. The monopile, which project above the water surface is robust structure that lowered into holes drilled in the sea bed and then grouted in place. Site preparation is required to avoid scouring [56]. In [58], the authors have proposed the idea of ship propeller wash on the

ports of Straits of Malacca to avoid seabed scouring. The proposed foundation for FTT is a steel mono-pile structure. The reason can be attributed to that the mono-pile structure confronts relatively low sea scouring and is sufficient to support the light weight FTT.

3.3. Performance

The performance of a tidal turbine can be arbitrated by the theoretical efficiency, tip speed ratio, solidity and pitch control. The tip speed ratio is normally fixed for the CTT, but FTT has an adaptable tip speed ratio. The extensible rod can change the diameter of rotor to produce different tip speed ratios. This leads to changes between the performance of folding and conventional tidal turbines.

3.3.1. Theoretical efficiency

Theoretical efficiency of FTT depends upon the similar parts as of CTT i.e. gear box, generator, frequency convertor and transformer. Efficiency given by the aforementioned elements is mostly same for all type of turbines. For FTT, these can be taken as the efficiency of gear box, generator, transformer and frequency convertor with performances of 90%, 95%, 98% and 96% respectively. Hence, the theoretical efficiency of FTT will be expected as 86% with multiplication of all the aforementioned values of efficiencies [59]. The power co-efficient for vertical axis tidal turbine is 0.2 [60]. Thus the turbine efficiency will drop to 17.2%.

3.3.2. Tip speed ratio

The tip speed ratio of a three-bladed vertical axis CTT varies from one to two for power coefficient of 0.2 [61]. The tip speed ratio can be optimised in FTT by changing the diameter of a turbine in response to changing speed of water at various sites. The blade tip speed depends upon the diameter which can be varied. FTT can be folded up to half of the installed size [62]. Thus the tip speed ratio can be reduced to avoid the corrosion of the blade tip for high water velocity sites. Multiple configurations are possible by adjusting the extensible blades, connecting rods and shafts. The weight of FTT rotor blade is designed to be lighter than CTT. A lighter weight results in a higher rotor speed. The tip speed ratio can be controlled automatically via remote control ideally.

3.3.3. Solidity

The term solidity describes the ratio of the total area of the blades to the area swept. It depends upon the number and dimensions of each blade. Solidity of vertical axis tidal turbine increases with the drop in tip speed ratio [63]. Solidity of any structure provides an idea about the stability and reliability of the system. Normally the solidity is described as in Eq. (2).

$$S = (n \times A_p)/A \quad (2)$$

here n is the number of blades, A_p is the surface area blade and A is the flow contact area. Another way of calculating solidity is proposed by Ricardo A. Bastianon in [64]. The mechanism of both wind and tidal turbine is same and no density is included in this calculation. According to Ricardo solidity can also be calculated by Eq. (3)

$$S = (0.872/\sigma) – 0.086 \quad (3)$$

here S is the solidity and σ is the tip speed ratio. Assuming the tip speed ratio to be 5 for FTT, the solidity will be 0.08. The solidity of vertical axis CTT is also calculated by Guang Zhao and co-workers in [65]. The study was done both experimentally and numerically on a three blade vertical axis tidal turbine in a towing tank and the calculated solidity was 0.1146. A study done on NACA 0018 and NACA 633-018 has shown that solidity for a vertical axis turbine was as low as 0.06 when the tip speed ratio was 2–7. However, the solidity is was high for the tip speed ratio in the range of 1–2. In case of FTT the tip speed ratio can be varied, thus the solidity can also be regulated. In case of horizontal tidal turbines solidity ratio is lower for SeaGen while it is high for Open Hydro [66].

3.3.4. Power regulation

Power regulation is needed to protect the turbine during the high velocity flow. The high velocity flow generates excessive forces leading to the potential failure of components. The exerted forces on blades may cause blade damage especially during storm [67,68]. Turbines are therefore designed with a cut off speed to slow down the turbine for the protection purpose. Pitch control and stall control are commonly applied for power regulation in tidal turbine.

Pitch regulation is an active control system where the rotational speed of turbine can be controlled by changing the pitch angle of blade to protect the turbine. This method is called an active system as the system is still producing power with a higher fluctuation rate during the control. In stall regulation, the power production is being stopped when the rated flow speed exceeds the proposed velocity. This method is called as passive control. SeaGen has a fixed rotor with variable pitch controlled blades [69]. The pitch can be changed to 180° to harness the currents from different directions on ebb or flood tide. The advantage of FTT is that during extreme conditions of storm, no power regulation is required. This protects the blades and system from destruction. Hence, the problem of power regulation is solved. The power regulation system of FTT can be categorised as a passive power control system.

3.4. Installation

The procedure to unfold a FTT is illustrated in Fig. 7. FTT is designed not as heavy as the other tidal turbines. A pulley can be used to aid in dropping the FTT into the sea-bed. The outer box of the turbine opens up and the turbine can be connected to the pulley. Once the turbine reached the seabed, the nuts and bolts are fixed up. This makes a stronger and stable base. After that, shaft, connecting rods and blades are being opened up in sequence. The unfolding procedure make the installation completed and is ready to perform. Fig. 8(a) and (b) shows the folded and unfolded tidal turbines respectively.

3.5. Maintenance

Maintenance of tidal turbines is always an issue for both the large and small turbines. The turbines are located inside the water and the formation of biological films and corrosion of parts is a

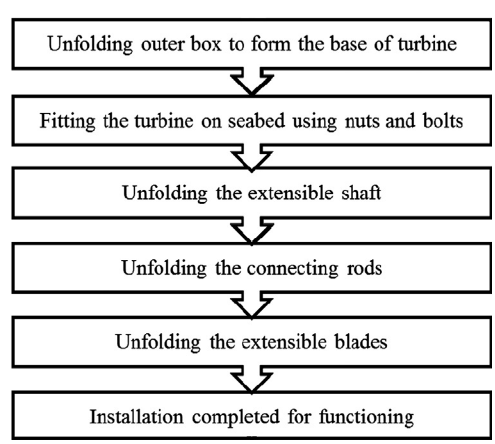

Fig. 7. Installation procedure of FTT.

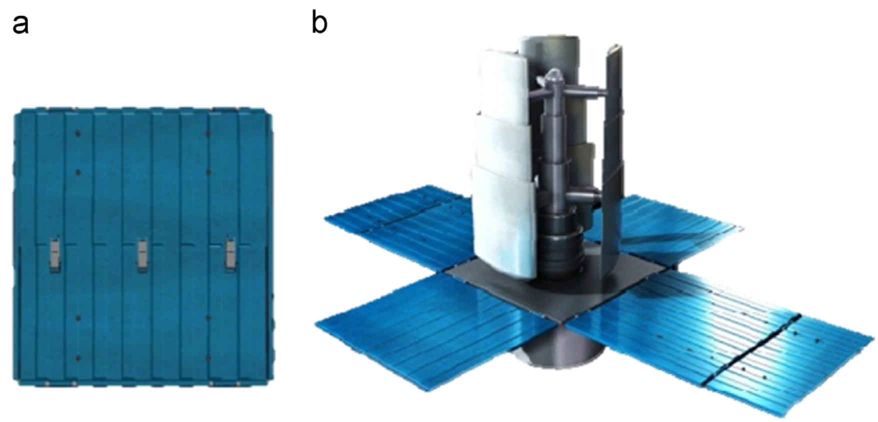

Fig. 8. (a) Folded turbine during transportation; (b) Unfolded turbine during installation.

Table 1
Description of tidal turbine cost.

Component	Description
Structure	FTT is expected to be more expensive due to the complication in manufacturing. The manufacturing cost of FTT is higher compared to CTT for the extensible feature of blades, connecting rods and shaft. The insertion of chips for remote control purposes increase the production cost of structure. Rotor consists of 20% of the total cost for a wind turbine [74]
Gearbox and drive train	Drive drain transfers the rotational forces to gearbox. Rotor is initially rotating at a low speed of approximately 10 rpm. Gearbox is used to speed up the rotational speed to be approximately 2000 rpm to satisfy the requirement of electricity generation. The expected gearbox and drive train are analogous for both FTT and CTT. It has not much cost differences for gearbox and drive train
Generator system	Both turbines are assumed to have the same power. An analogous generator is used for both of the turbines. FTT uses an induction generator as SeaGen
Foundation	Foundation/ support structure costs around 10% of the turbine's total cost. Size and weight of the support structure plays a major role in construction. FTT is designed to be lighter compared to CTT and therefore the foundation cost for FTT should be lesser
Transportation	Transportation procedure is complicated due to the large size of CTT. Driver with qualification, experiences and skills is required for the transportation. Audit of transportation is conducted to prevent any accident. FTT is designed to be smaller and lighter. The transportation cost of FTT is expected to be cheaper compared to CTT
Installation	FTT is designed to be a compact unit, which is easy to install. Installation of FTT is cheaper and faster compared to CTT. Fewer divers are required for the FTT installation in the harsh underwater environment
Operation and maintenance	Maintenance costs of CTT is estimated 3–5% of the capital investment per annum [75]. FTT is designed to have size control at different tidal period in order to maximise the energy output. These sophisticated features may increase the maintenance cost. FTT may need to include the maintenance cost due to folding failure of a turbine

general problem. The repair of turbines requires highly skilled manpower that can dive under water [70]. This problem is solved in FTT. There is no need of sending skilled divers into the water to perform maintenance. However, FTT can be folded up and can be easily lifted to the surface and can also be brought back to the shore easily. The maintenance process is cheaper for FTT in comparison to the CTT as less count of divers are required to fold it back and to connect it with the pulley. The process of installation is comparatively faster.

The manufacturing process for parts of FTT is a costly issue and the repair of these parts is equally expensive. The weather conditions at shore are generally harsh. Hence, maintenance at offshore is difficult and for this reason, transportation of the equipment is required. Due to the harsh weather conditions and limited access during operation, it may result in breakdown of turbine. This requires more time for servicing as repairing is not possible inside the water [71,72] The small size and folding characteristics make the transportation and offshore repairing feasible and easier.

The repair of the turbine may take long time. The reliability of operation is debatable. These cases are valid for all types of turbines including FTT. Hence suitable strategies are required for proper operation and maintenance. The coating material used to prevent the turbines from corrosion, has a protection time and an annual wastage rate. Timely inspection through ultrasonic waves and other techniques is required to check corrosion from time to time [73].

3.6. Cost

The cost of turbine varies significantly with the size, site and type. The comparison is made based on the 1.2 MW SeaGen and the proposed 1.2 MW FTT. The concept of tidal turbine was inspired from the wind turbine with similarities inherited [45]. The main components and associated expenditures are common for both the wind and tidal turbine. In [74] the authors have given a percentage based cost to all the components of the wind turbine. However, with these components expenditure on transportation, installation and operation & maintenance (O & M) also plays a vital role. Cost comparison of CTT and FTT based upon the various factors is shown in Table 1.

From the 7 factors discussed in Table 1 the cost involved in generator, foundation and gearbox is size dependent, thus for the same size and site there will be no marginal difference in them. The important factors here are the structure (rotor), O & M, installation and transportation. The cost involved in structure and O & M will be higher for FTT, while the expenditure on transportation and installation will be higher for CTT.

Hence, the utilisation of FTT is more appropriate for the sites where the difficulty in transportation as well as for installation is higher. Table 2 shows the cost estimation of FTT compared with CTT, based on the above mentioned features. Fig. 9 is the graphical representation for the same. It is remarkable to not that this is just an estimated idea and the actual cost may vary compared to the present study.

3.7. Environmental effects

The concept of tidal current turbines was introduced to meet the growing demand of electricity and to reduce the harmful effects of fossil fuels. The fuel used for tidal current turbines is the water. Hence, unlike fossil fuels it does not emit harmful gases during the operational period. However, to judge the environmental effects, researchers count the CO_2 emitted during the transportation of turbine and its components. Transportation of large turbines requires number of vehicles. Thus, reducing the size of the turbine will make it feasible to transport higher number of turbines to the site, using lesser number of vehicles and thus the air pollution will be reduced. Installation of the turbine on/inside the water surface leaves an impact on the ecosystem. The environmental impacts are shown in Table 3.

Table 2
Cost comparison between FTT and CTT.

Elements	Estimated cost breakdown of CTT [74] (%)	Estimated cost breakdown of FTT (%)	Differences between CTT and FTT
Structure	40	45–60	Increment
Gearbox and drive train	10	10–20	Increment
Generator system	5	5–10	Increment
Foundation	10	5–10	Reduction
Transportation	10	5–10	Reduction
Installation	20	5–10	Reduction
Operation and maintenance	5	5–10	Increment
Total cost	100	80–130	

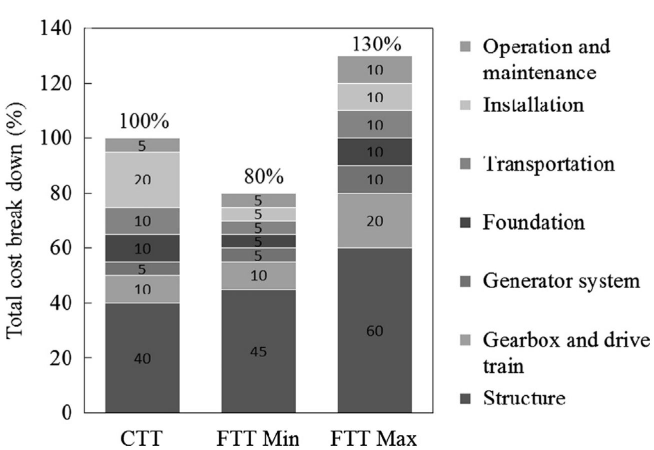

Fig. 9. Comparison of cost breakdown between CTT and FTT.

3.8. Electrical aspects

Electrical loading and power transmission are two important aspects for the electrical consideration. These two aspects are discussed in the following sections.

3.8.1. Electrical loading

Electrical loading refers to the amount of power it can support or the load, which can be connected to it. The complexity of FTT system leads to the higher chances of malfunctioning. From Eq. (1), the power output is proportional to the cube of flow velocity. Hence, small variation in water speed gives significant impact to the power fluctuation. Therefore, an auxiliary system is required to produce smooth power output.

3.8.2. Power transmission

The generated electricity can be produced through the cable transmission. The underwater cable connects to offshore substation and then to the users. Electricity is being stepped up using transformers to compensate the losses due to transmission as CTT.

4. Distinctive features of FTT

Folding and conventional tidal turbines both are proficient from performance perspective. Nevertheless, some of the features of FTT are different from CTT. The rotor diameter is adjustable and smaller in FTT. The adjustment of rotor diameter gives the provision of adjusting the tip speed ratio and the solidity of the turbine. The lighter weight of FTT is the result of lower turbine size. Owing to the smaller size, the rotor fluid velocity of FTT is lower approximately 2 m/s. The lower rotor fluid velocity delays the corrosion of the blade tip. As a comparison, the rotor fluid velocity of CTT is approximately 2.6 m/s.

The power regulations of both tidal turbines are different too. FTT does not require any pitch angle of the blade however for CTT the maximum pitch rate observed is $\pm 6^{\circ}/s$ [58]. The characteristic of automatic power generation may avoid cost associated with equipment damage and downtime due to poor voltage levels.

The support used or the foundation structure of FTT and CTT is distinct too. FTT uses a mono-pile structure while CTT uses a tripod structure. Mono-pile structure is designed for FTT owing to its smaller size and lighter weight. Therefore, a mono-pile structure is sufficient to stabilise the machine. A tabular comparison of the features of folding and conventional tidal turbines is shown in Table 4. The data used for CTT in Table 4 is for a horizontal axis turbine.

5. Opportunities and challenges

FTT is potent to be introduced to the tidal turbine market due to its smaller, lighter and flexible features. Transformation of tidal

Table 3
Environmental impacts of FTT.

Potential impacts	Description
Physical damage	The rotating turbine may strike the aquatic life directly even the moving speed is slow [76]
Chemical pollution	CaviTec [55] is proposed for blade protection to minimise the effect of bio-fouling. The leaching of the protective layers for anti-corrosive or anti-biofouling gives unknown effects to the ecology system
Underwater noise	Transportation, installation, maintenance and operation of FTT produce underwater noise. It may give effects to aquatic life for seeking direction, reproduction, prey and communication [77]
Electromagnetic impact	Tidal power is transmitted through underwater cables. These cables emit low frequency of electromagnetic fields. Although the cable is designed to minimise the direct emission of electromagnetic field. However, the influence of electromagnetic field to aquatic life is remained an unknown

turbine design is a crucial and ongoing task undertaken by the researchers in order to harness maximum tidal energy with minimum resources and material. The FTT has some remarkable characteristics which make it contributable to the industry of marine renewable energy. However, the concept of FTT is novel and needs deep research in various fields to make it appropriate for various sites. Tables 5 and 6 explain the strengths and weaknesses of FTT. The novel design of FTT has various benefits. The advantages of FTT are summarised in Table 5. Even though FTT has many advantages, there are several challenges faced. Researchers concern towards the durability of FTT due to several reasons as Table 6.

Table 4
Comparison between FTT and CTT.

Parameters	FTT	CTT [59]
Dimension	24 m in height and 16 m in diameter	18 m
Number of blades	2–10	2 or 3
Rotor fluid velocity	2 m/s	2.6 m/s
Power regulation	Automatic	Pitch
Maximum pitch rate	None	$\pm 6^{\circ}$/sec
Support structure	Mono-pile	Tripod
Structural flexibility	Foldable	Rigid
Swept area of blade	360°	300° to 320°
Folding capacity	Estimated half of unfolded size	None

6. Conclusion

As FTT is a novel concept and does not possess many studies in this area, there are various fields and parts in which further improvement is needed. The use of gearbox makes it heavy and unsuitable for low speed sites. Moreover, DFIG is not suitable for all the sites. Hence, efforts are required to make it suitable for all the sites irrespective of the water velocity. But, it is an assured fact that problems of transportation, installation and more turbines in a single channel will be sorted out. Thus, with the fabrication of FTT, the other aspects including actual efficiency and rotation per minute (rpm) will become calculative. Hence, with the exact figures of these fields, FTT will help to judge about the idea of energy produced by it. From the above study, it is obvious that the advantages of FTT are leading its loopholes. Defects such as high cost in remote control and corrosive folding part may be decreased through a number of trials and errors. These may be a researchable topic of future studies since the FTT has a bright prospect in harnessing more power as long as the defects are resolved.

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Table 5
Strengths of FTT.

Feature	Description
Foldable	FTT is designed to be foldable into a smaller unit compared to its unfolded state. Blades, connecting rods and shafts can be folded into a single box. Smaller size is easier and cheaper in transportation
Extensible	Blades, connecting rods and shaft are designed to be extensible. Extensible feature makes FTT easier to be carried and transported
Simple installation	Installation of FTT is simpler compared to CTT. FTT is designed to be lighter and simple in installation. Folded FTT can be sent to seabed with hook and pulley. FTT can be unfolded after fixing the opened outer box onto the seabed. It can reduce the cost for expensive divers and setup time
Easy transportation	FTT is easier and cheaper in transportation compared to CTT due to its smaller and lighter design. CTT requires the qualified and skilled transporter, subcontractor and quality manager in the process of transportation [78]. However, shock attenuation system is also required for safe transportation as CTT.
Adjustable tip speed ratio and solidity	The change of length of connecting rods makes a different turbine diameter and subsequently makes the tip speed ratio and solidity adjustable. Tip speed ratio is able to be adjusted according to the tide cycle and characteristics of sites
Cheaper in remote area	FTT reduces the costs of transportation and installation. Remote area may require expensive transportation and installation. FTT is expected to be cheaper in remote area compared to CTT
Faster setup time	FTT is designed as a compact, smaller and lighter unit. The setup time of FTT should be faster compared to CTT
Emergency purpose	FTT is a good choice to harness tidal power in emergency condition. FTT is easier to carry and faster to setup compared to CTT. Rescue team or army may be interested on FTT
Better for installation in constricted area	FTT is suitable to the constricted area where the large installation machine is difficult to be placed. Placing a small unit into the constricted area is easier compared to a full unit. FTT can be unfolded once the installation is completed

Table 6
Weaknesses of FTT.

Feature	Description
Folding failure	Folding failure is the unique consideration of FTT compared to CTT. Intrusion of algae, foreign object and high level of corrosive layer may cause failure on folding up the particular components
Manufacturing cost	The extensible feature of blades, connecting rods and shaft may increase the manufacturing cost. Chips are required to enable remote control features for the extensible components
Maintenance cost	FTT is designed to control the tip speed ratio and solidity remotely through the extensible features. Maintenance cost for remote control is an unique cost, which may not found in CTT. Maintenance cost is expected to be higher than CTT
Corrosion	FTT consists of connected parts that can be folded up. These connected elements may be vulnerable for corrosion. The corrosion can be overcome through the anti-corrosive painting and regular maintenance
Power regulation	FTT has the common problem as CTT. Power regulation is needed to slow down the rotor during extreme flow speed
Generator	FTT is recommended to use DFIG as CTT. DFIG requires more maintenance and more difficult in complying grid code
Environmental effects	FTT has environmental impacts as CTT as discussed in Section 3.7

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